#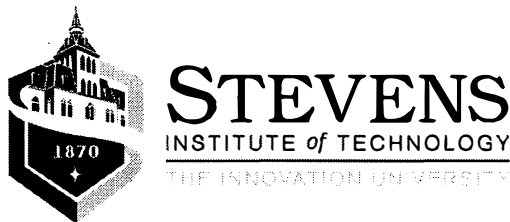 Use of Forward Scattering Particle Image Velocimetry to Quantify a Flow Field Near a Fully Submerged Tension Leg Platform in the Presence of Waves

STEVENS
INSTITUTE *of* TECHNOLOGY
THE INNOVATION UNIVERSITY

Submitted to

Dr. Ronald Joslin
Program Officer, Code 331
Office of Naval Research

2010 Technical Activities

Fundamental research of flow fields over fully submerged platforms initiated in April 2010. The first research task in 2010 was to evaluate the use of particle image velocimetry (PIV) to record a 3-D flow field from particle images in a 2-D plane over a fully submerged tension leg platform (TLP). The preliminary tests were set up to determine if PIV images of a flow field over a 1.2m (4ft) wide platform would provide useful data in a large wave tank facility (95m long x 5m wide x 2.4m deep). The use of PIV images involves a trade-off between field of view and resolution, as field of view increases, resolution decreases. A technician from the vendor of the PIV system used for this experiment, Dr. Steve Anderson of LaVision Inc., was initially skeptical about our attempts to use PIV to analyze a 0.5m x 0.5m flow field over a fully submerged TLP. The use of the forward scattering PIV configuration exceeded the expectations of Dr. Anderson suggesting fields of view larger than 0.5m x 0.5m can provide useful image data using a forward scattering technique.

Fully Submerged TLP – Preliminary Tests

A fully submerged 1.2m wide TLP was moored near the surface of Tank 3 at Stevens Institute of Technology to generate changes in the wave form and flow field over the TLP in various wave conditions (Fig. 1). The laser sheet generator of the PIV system can be seen on the left side of the wave tank, and the down tube for camera 2 can be seen on the right side of the red bridge spanning the wave tank in the forward scattering configuration.
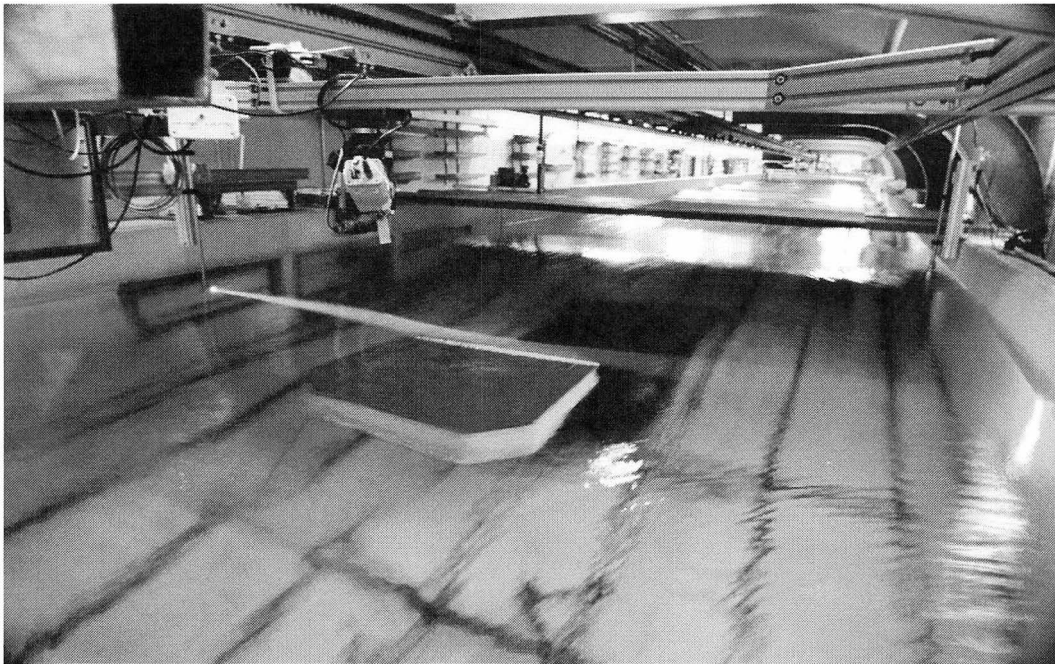
Figure 1: A PIV Laser Light Sheet Illuminates Particles over a Fully Submerged Tension Leg Platform in the Presence of Waves.

Experimental Studies at Stevens Institute of Technology

The low density, full submerged TLP has been tested at depths ranging from 15cm to 110cm and large amounts of PIV and wave-wire data were collected and processed in 2010. The PIV data allowed us to analyze the flow pattern and changes in wave form as incident waves passed over the surface of the TLP. Each wave run generated 80 images of the flow field from each of two cameras; Camera 1, "downstream" (relative to wave propagation) of the platform and Camera 2 "upstream" of the platform sampling at 15Hz. Total capture duration was 5.33 seconds per run.

Experiment Set Up and Results

Stereo Dual Camera Calibration:

Before the PIV testing could be carried out, an accurate calibration of the PIV camera array was needed. This calibration was required to correct for the off-axis viewing of each of the cameras, and to produce measureable "corrected" images from which the user can collect useful particle velocity information. The calibration scaled the resulting images to represent the dimensions in the plane of the laser light sheet.

The Calibration Wizard in La Vision's DaVis 7.2 imaging software suite was used to complete the camera calibration. The wizard guides the user through the calibration process and verifies an accurate calibration.

A two-level calibration plate was used to calibrate the stereo PIV camera array. Each side of the plate was etched with silver calibration triangles and squares arranged in a known three dimensional arrangement across two levels. This two level array simplified the camera calibration by providing the PIV system with multiple calibration planes without having to move the plate.

The calibration plate was aligned with the laser sheet in the field of view of the cameras. The wizard captured images of each side of the plate using the stationary PIV cameras. These images can be seen in Figure 2. The wizard prompted the user to define basic information about the plate and to identify three of the calibration marks on either side of the plate. With this information, the PIV system was able to identify the remaining calibration marks, fit a mapping function to the image, scale the images and complete the calibration process. The resulting in-plane images are shown in Figure 3.
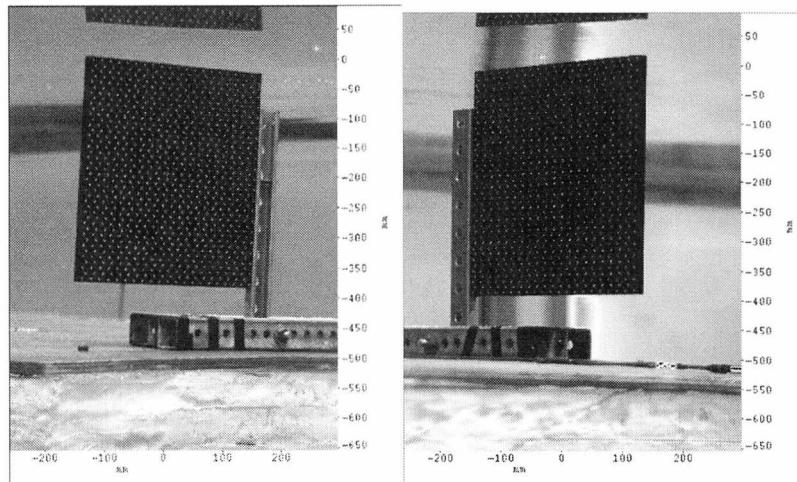
Figure 2: Photos of calibration plate 15cm from the "leading edge" (facing incoming waves) of the platform from Camera 1 (left) and Camera 2 (right)
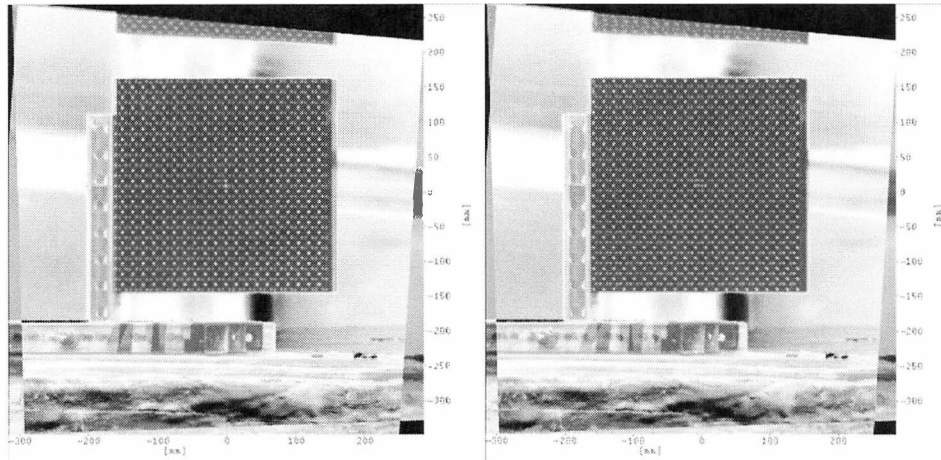
Figure 3: Calibrated in-plane images from Camera 1 (left) and Camera 2 (right)

Wave Wire Calibrations:

Two wave wires were used for the 2010 experiments. One was placed 6.25m upstream of the laser and one was placed 2.70m downstream of the laser directly behind the platform to measure the waveform changes due to incident waves passing over the platform. Each wave wire was raised and lowered 7.5cm above and below the still water line in increments of 2.5cm, and voltages were recorded at each elevation to provide the calibration relationship between water depth and wave wire voltage output. Both wave wires were nearly linear over the range of calibrated elevations.

Processed Data
The data processing method for one of the eighty-nine PIV runs during the first test
matrix in 2010 is described in this section.

6.1cm (2.4in) 2s Waves with 30cm Platform Depth
For this run the waves created were 6.1cm (2.4in) high with 2 second periods. The time
histories of the waves before, over, and after the platform can be seen below (Fig. 4).
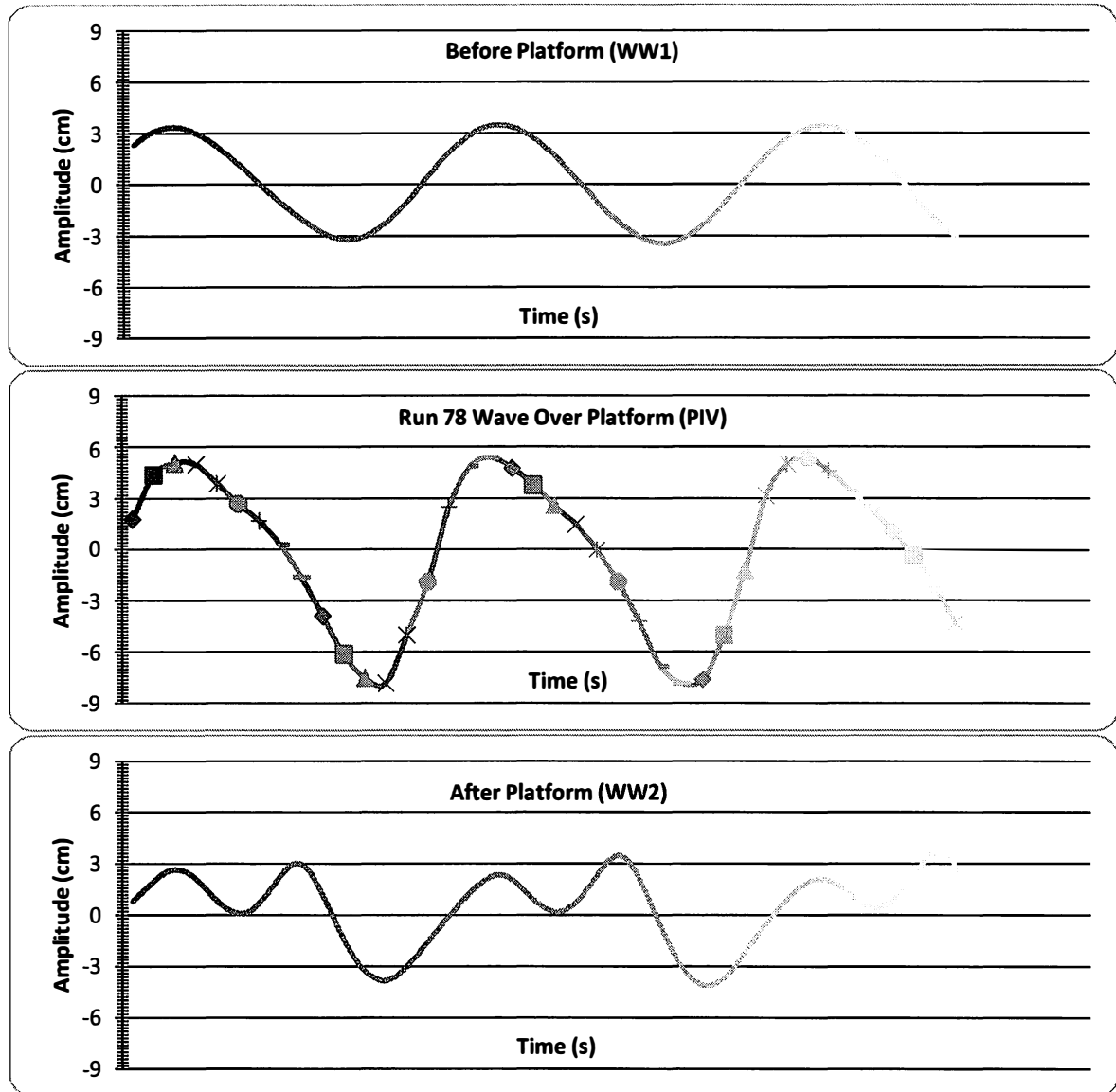
Figure 4: Time histories of wave amplitude before, over, and after the platform

The plots in Figure 4 show the wave heights were more than doubled over the platform to
create 13.2cm (5.2in) waves. Approximately 2.54cm (1in) of height was added to the

crest of each wave and 4.57cm (1.8in) were added to the trough of each wave. The offset may be due to set-down of the still water line which appears to come from platform motions. Wave parameters were estimated using linear wave theory. The time between wave crests at WW1 and over the platform are nearly identical, but the waves collapse into a spectral form downstream of the platform with periodic variances from the still water level which are slightly larger than the incident waves.

Water Density = 1000 kg/m^3
Acceleration due to Gravity = 9.8 m/s^2
Wave Wire 1:
Water Depth = 1.98m, Wave Height = 0.061m
Wave Period = 2 seconds, Wavelength = 6.04m
Energy Density = 4.56 Joules per square meter of wave profile
Wave Power = 7.80 Watts per meter of wave crest
Over the Platform (PIV)
Water Depth = 0.30m, Wave Height = 0.132m
Wave Period = 2 seconds, Wavelength = 3.25m
Energy Density = 21.34 Joules per square meter of wave profile
Wave Power = 31.39 Watts per meter of wave crest

The wave transformation resulted in a 4.02 fold increase in wave power concentration over the platform. At full scale (10x geometric parameters), wave power concentration is estimated to increase from 2.53kW per meter of wave crest to 10.17kW per meter of wave crest in standard seawater.

The following diagrams show the corrected images and vector diagrams for one wave cycle, crest to crest, as a 2 second, 6.1cm (2.4in) wave passes over the platform at a 30cm depth (Figs. 5-11). For estimating wave heights during this run, the free surface was tracked at -310mm along the x-axis (far left edge of the corrected image).
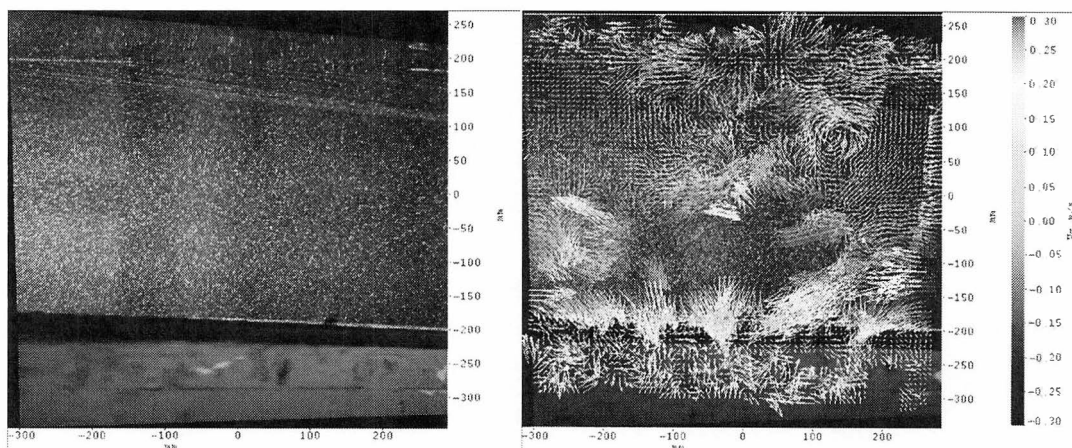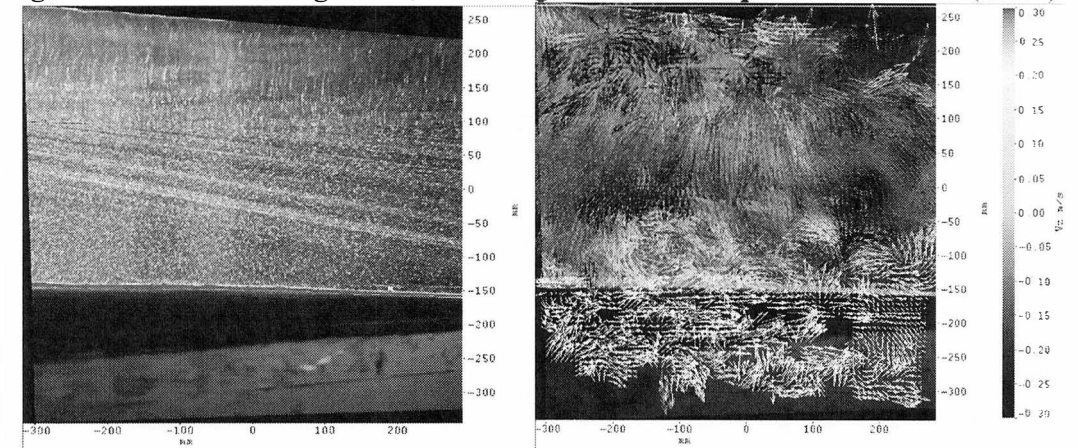

Figure 5: Corrected image (left) and vector diagram (right) - wave amplitude of 5.33cm (2.1in) (Wave Crest)
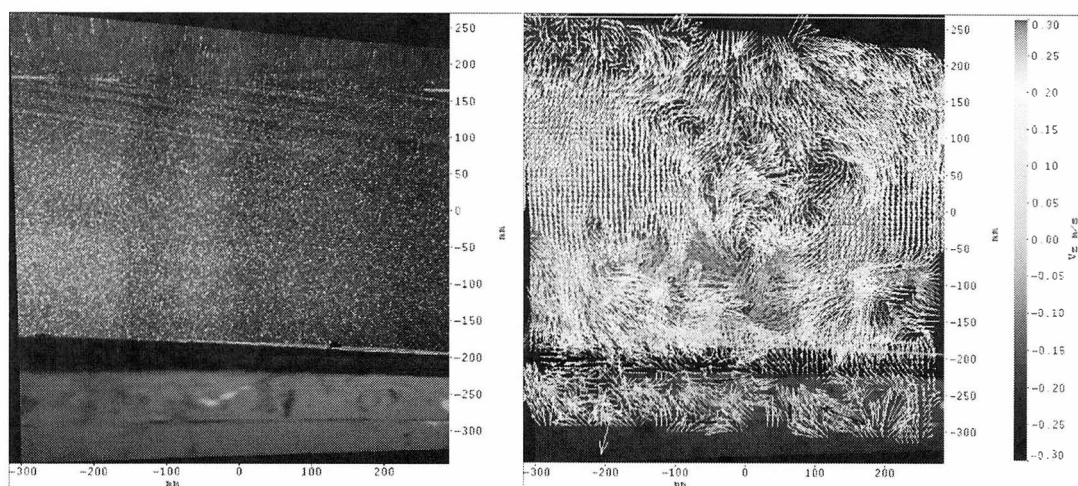
Figure 6: Corrected image and vector diagram - wave amplitude of 3.3cm (1.3in)
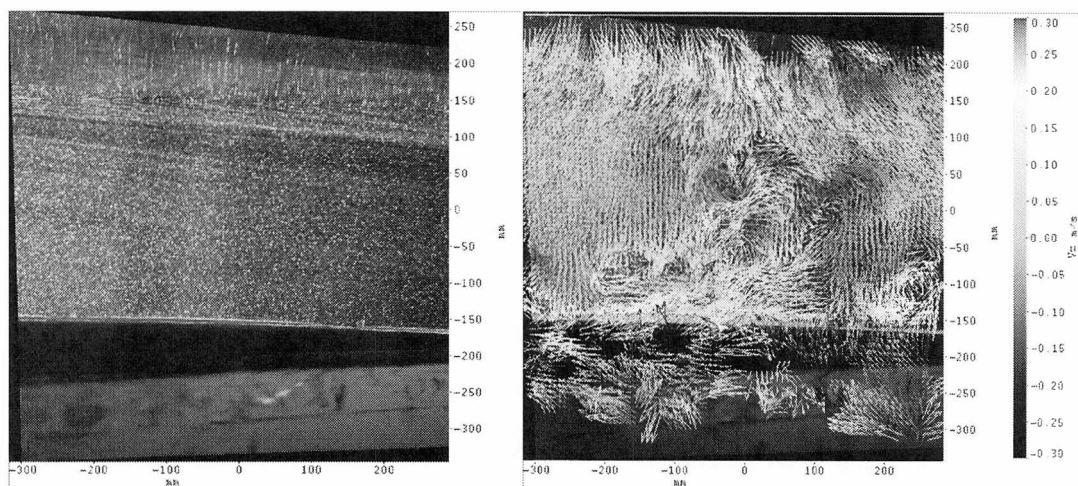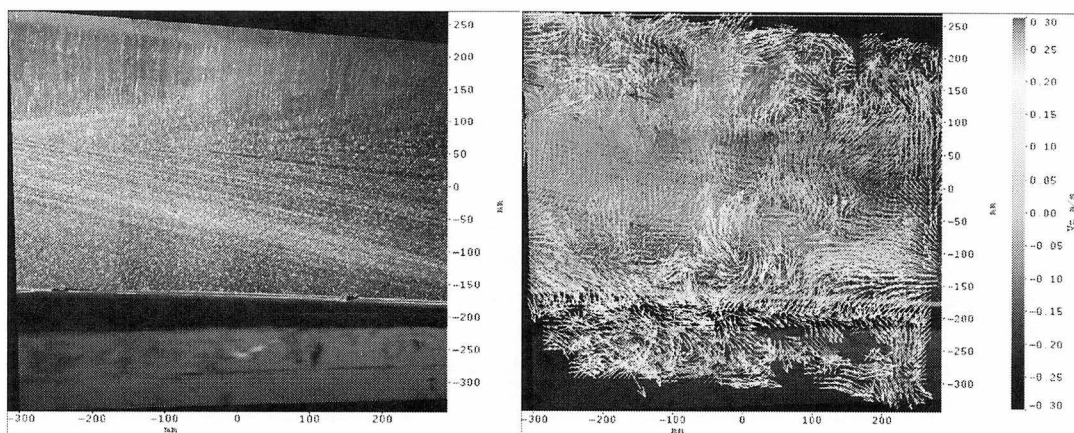

Figure 7: Corrected image and vector diagram - wave amplitude of 0.25cm (0.1 in)
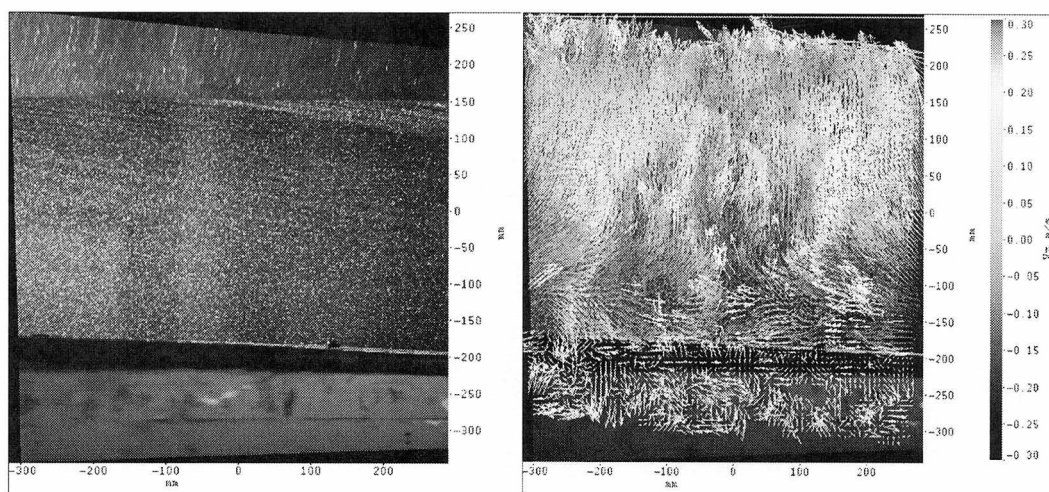

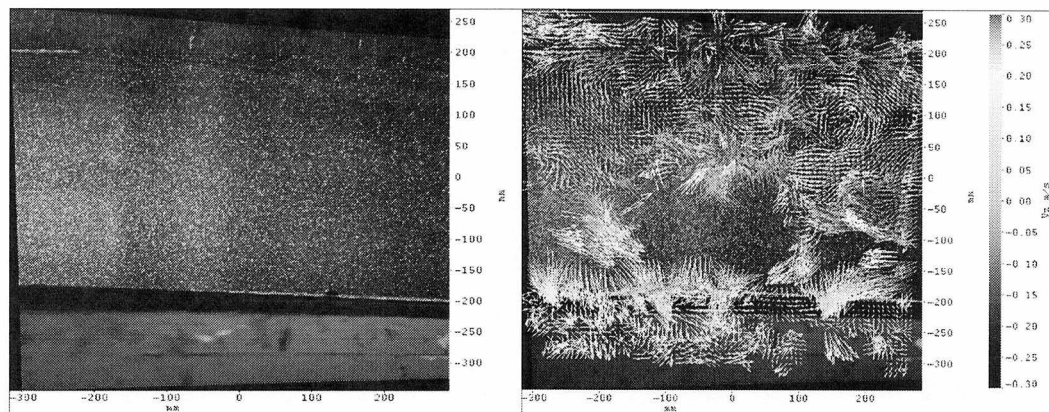**Figure 8: Corrected image and vector diagram - wave amplitude of -4.83cm (-1.9in)**

Figure 9: Corrected image and vector diagram - wave amplitude of -7.87cm (-3.1in) (Wave Trough)

Figure 10: Corrected image and vector diagram with wave amplitude of 0.25cm (0.1in)

Figure 11: Corrected image and vector diagram - wave amplitude of 5.33cm (2.1in) (Wave Crest)

The vector diagrams in Figures 5-11 are overlaid on the corrected images. Each vector is assigned a magnitude (length), direction (arrowhead), and color (out-of-plane velocity scale). Heave (up and down) and sway (left and right) components of each particle are quantified by arrow length and direction, and the surge (forwards and backwards) component of each particle is quantified by color code. Bright red to white vectors indicate the highest out-of-plane particle velocities towards the beach-end of the wave tank, and dark blue or black vectors indicate the highest out-of-plane particle velocities towards the wave paddle.

2011 Technical Activities

Fundamental research of flow fields over fully submerged platforms continued in 2011 after processing PIV data from 2010. One of the main objectives of this research is to develop and validate Computational Fluid Dynamics (CFD) software programs for use in analysis of complex flow fields. After the 2010 wave tank runs, numerical models of the fully submerged TLP and wave tank used in the experiment were developed. The scope of the work in 2011 focused on validating the CFD outputs with data. Work proceeded to develop an experiment capable of measuring the platform motions and loads as these parameters were unknown to the CFD developers. Accelerometers were considered early in 2011 as a possible option. Faculty at the Davidson Laboratory decided to use position sensors vice accelerometers in the motion study to avoid drift due to integration of position (Figs. 12-13).


Figure 12: A 3-Axis position recording experiment was setup in Tank 3 at the Davidson Lab. Three potentiometers actuated by constant-force spring reels were used to measure platform positions in waves during the first test matrix in 2011. The lines from the spring reels were connected at a common point over the platform at the end of a 3/8" diameter threaded rod fixed to the platform. The threaded rod was extended above the water surface to enable use of these potentiometers. The spring reels lines were oriented in the surge (x-plane), sway (y-plane), and heave (z-plane) planes of the platform based on waves propagating from the bottom towards the top of this image and the potentiometer locations relative to the connection point were recorded to define the test space.
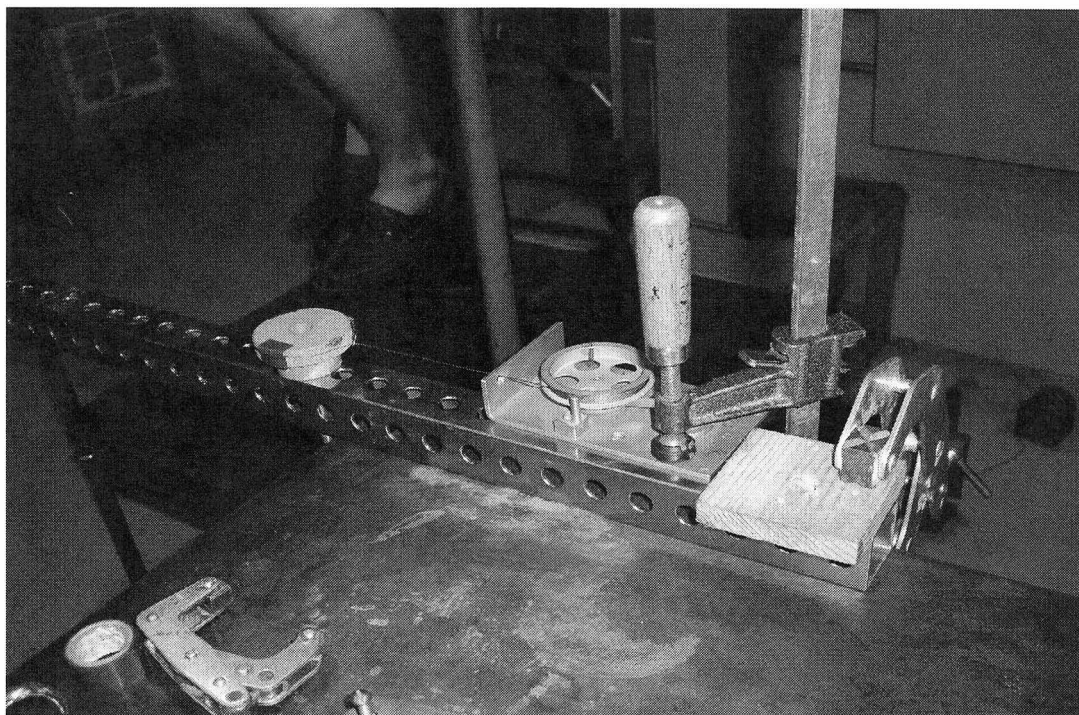
Figure 13: The potentiometers were calibrated using a perforated square pipe with holes at 1 inch (2.54cm) on center spacing. Voltage outputs were recorded over a 24 inch (61cm) range, wire payout to voltage output was recorded, and a voltage to distance conversion equation was fit to the data.

Load cells were added to the experiment to measure the varying loads on the mooring lines in waves (Figs. 14-15).
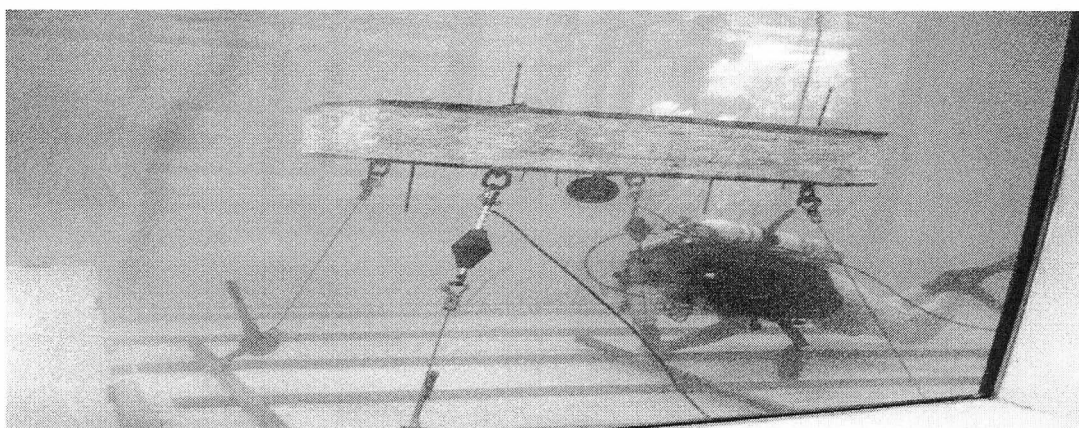
Figure 14: This image shows a 500lb load cell on the wave maker-side tension leg of a fully submerged TLP in the foreground and PI Raftery installing a 500lb load cell on the beach-side tension leg
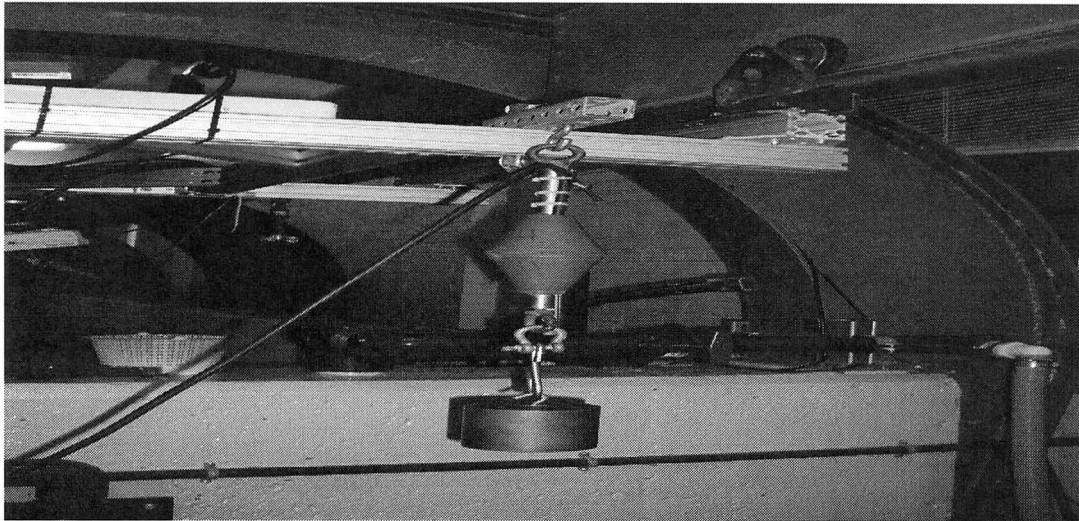
Figure 15: The load cells were calibrated using weights of known mass. Voltage outputs were recorded at various weights, voltage output was recorded for each weight, and a voltage to weight conversion equation was fit to the data.

The 2010 CFD work developed simulated position and load data based on simulated wave loads acting on the platform (Fig. 16). Position and load data from 1.5s – 2in (51mm) waves acting on the 30cm deep TLP in Tank3 were measured in 2011 to compare to the CFD outputs (Figs. 17-19)
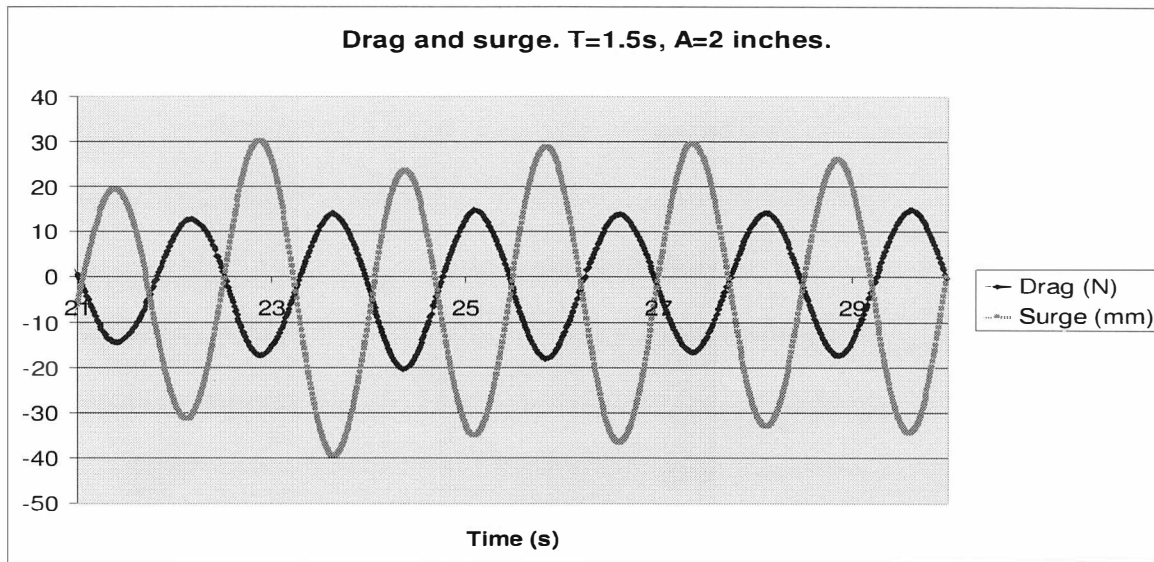
Figure 16: CFD outputs of numerical platform loading and response in 1.5s – 2in (51mm) monochrome waves at a 30cm platform depth
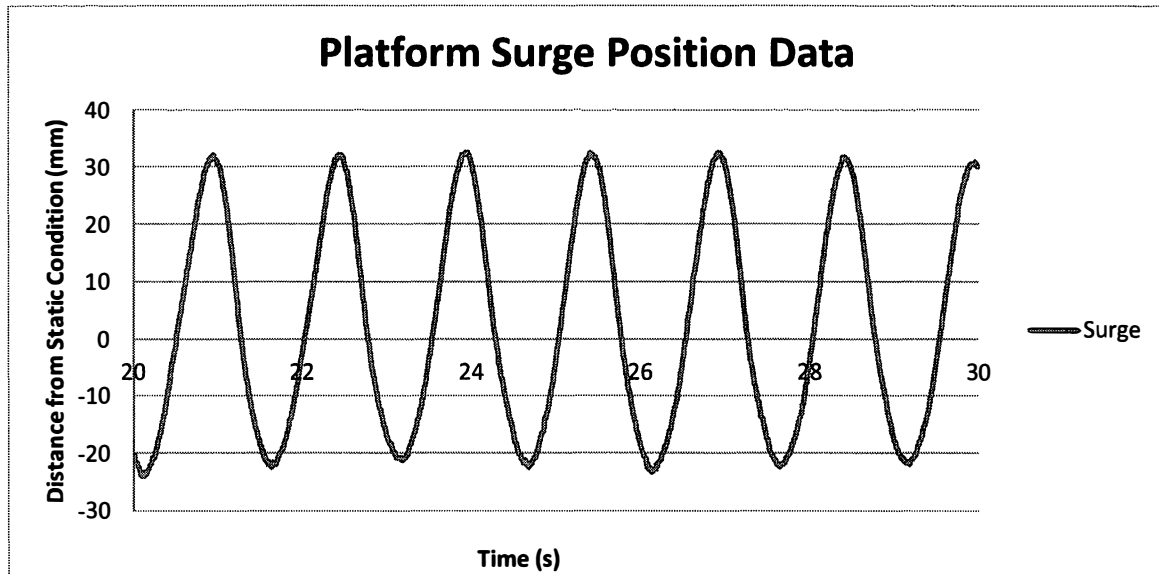
Figure 17: Potentiometer outputs of platform response to 1.5s – 2in (51mm) monochrome waves show a lower surge value than the CFD (55mm vice 60-70mm) with less variation. Platform surge is nearly equal to incident wave height
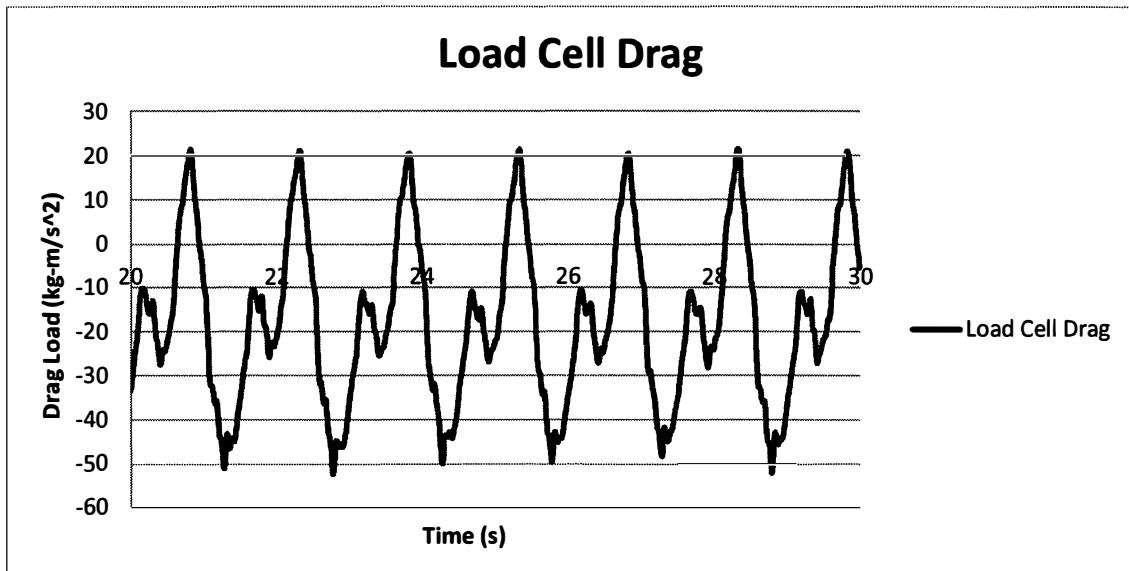
Figure 18: The data from the load cell on the beach side of the platform in the 1.5s - 51mm (2in) waves included harmonic events where the mooring line was partially unload for 0.3 seconds before the full load was returned to the mooring line. The drag load was calculated as the horizontal component of the total load on the mooring line, and the measured drag loads were significantly larger than the CFD outputs.

The potentiometer output in Figure 17 and load cell output in Figure 18 were recorded simultaneously with the wave wire output in Figure 19.
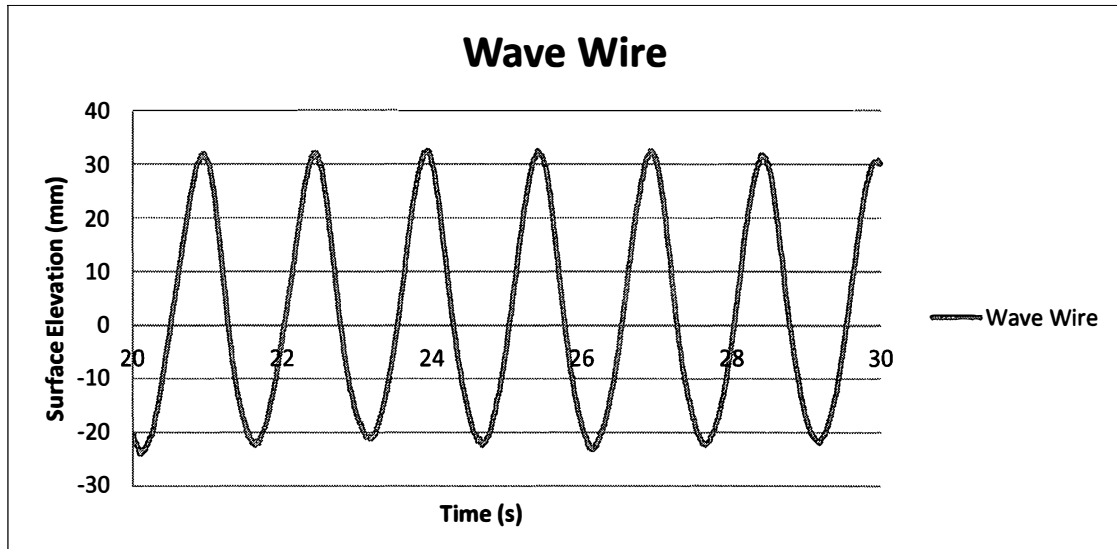
Figure 19: The wave wire output shows 1.5s - 51mm (2in) waves were incident at the platform during recording of platform surge in Figure 17 and mooring loads in Figure 18.

The phase adjusted CFD simulation of surge is fairly accurate with CFD outputs within 17% of recorded data points between the 23 and 30 second time periods in Figures 16 and 17. The CFD simulation did not capture the harmonic motions in the mooring lines (Fig. 18). The Numeca™ CFD program developed for this project has started out with some restrictions on simulated motions:

The numerical investigation developed by Romain Garo and Len Imas included:
- ❑ Numerical model:
  - 3D finite-volume / time-accurate discretization of the Navier Stokes equations
  - hexahedral mesh with local grid adaptation
  - free-surface capturing model using a BRICS VOF scheme
  - uRANS turbulence treatment using k-w SST model
  - generalized wave-maker boundary condition
  - n-DOF rigid body motion integrator coupled to hydrodynamic solver for simulation of TLP motion response to wave excitation
  - equivalent spring mooring system model
- ❑ Overview of investigation:
  - interaction between TLP and monochromatic waves
    - rigid body response
    - wave modification due to rigid body motions

- ❑ 4 different periods were investigated : 1.5, 2, 2.5 and 3 seconds.
- ❑ 4 different amplitudes : 1,2,3 and 4 inches.
- ❑ Constant platform depth of 30cm.
- ❑ The TLP is allowed to surge only.
- ❑ Some numerical damping is used near the outlet to avoid reflection of the waves
- ❑ 10 flow outputs per period

After reviewing the CFD outputs, PI Raftery has concluded the CFD program will require more development to model the flow field and platform motions with sufficient accuracy to contribute to the design process for fully submerged TLP systems. Validating CFD with data is a time intensive process requiring personnel trained in the development of software and experiments. Using a statistical method of validating CFD based on data was considered the only viable option in 2010, but the data-CFD comparisons from 2011 suggest the CFD may be improved in discrete steps based on parameters. If the CFD code can be adjusted to capture harmonic motions, the surge motion correlations may improve. CFD development concentrated on improving position or load simulation based on data will result in more robust CFD programs. Since wave height is used in numerous design equations in the field of ocean engineering, future work will focus on developing and validating CFD capable of resolving the free surface position changes in an area over a TLP vice a point or plane as measured in the 2010-11 work.

Further Project Developments

During the 2011 test matrix, a 30cm diameter, 2.7kg surface float was tethered to the fully submerged TLP at 30cm depth to simulate a generic wave energy conversion device with a load cell in line to calculate mechanical power acting on the float (Figs. 20-21).


Figure 20: A 30cm diameter, 2.7kg surface float with an in line load cell is tethered to a TLP using a spring reel. Position sensors are connected to the load cell.
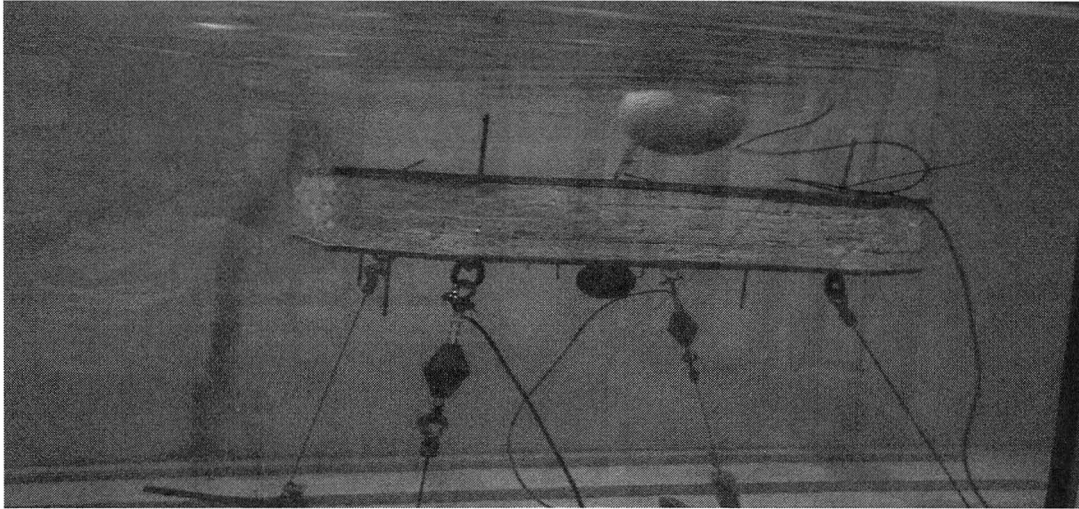
Figure 21: The 30cm float motion was mainly in the heave and surge planes with very little sway motion. The combined heave and surge motions were recorded as a position output from the heave wire. This image was taken in 1.5s – 1 inch (25mm) waves.

The heave wire position sensor measured 3.75cm float "pulses" from the static "0" location in 1.5s – 1in (2.5cm) monochrome waves towards the beach that would occur in 0.3 seconds (Figs. 22-24).
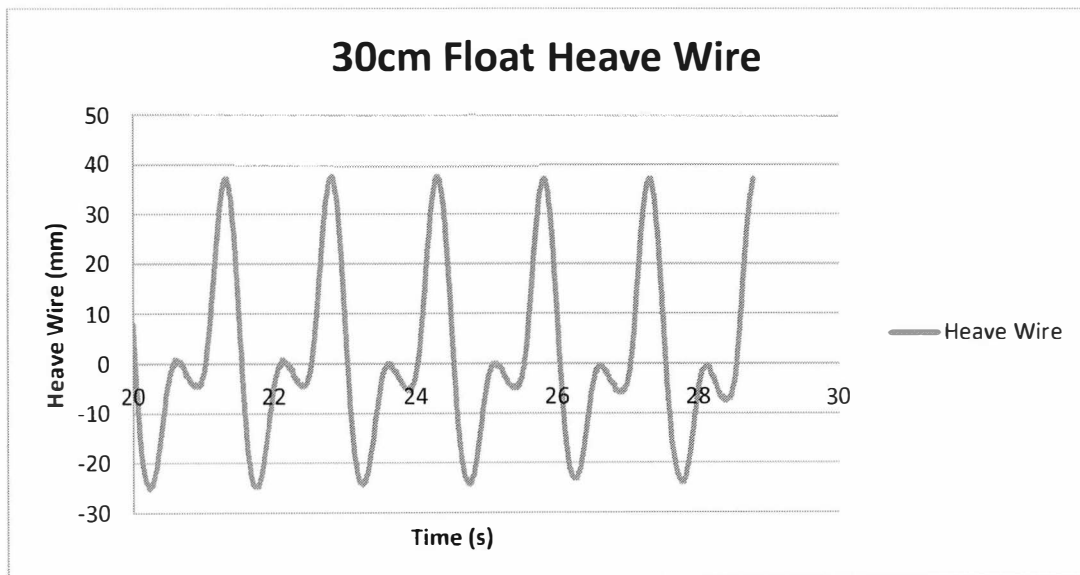
Figure 22: Heave wire position sensor measures float motion in 1.5s - 25mm waves
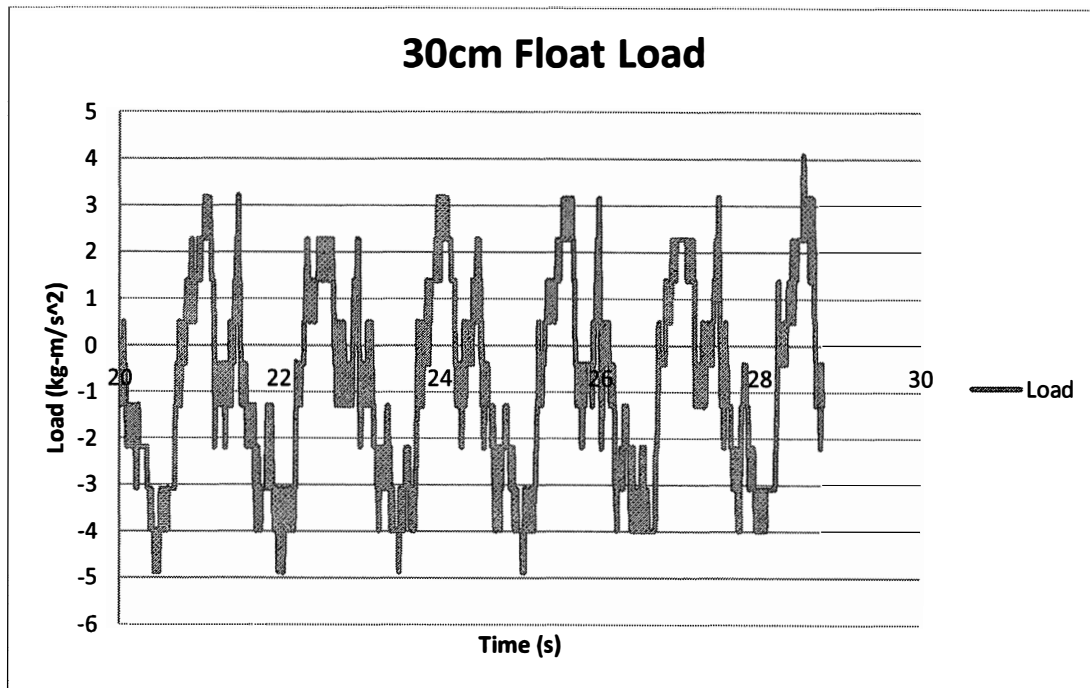
Figure 23: 30cm diameter float load cell outputs in 1.5s – 25mm waves
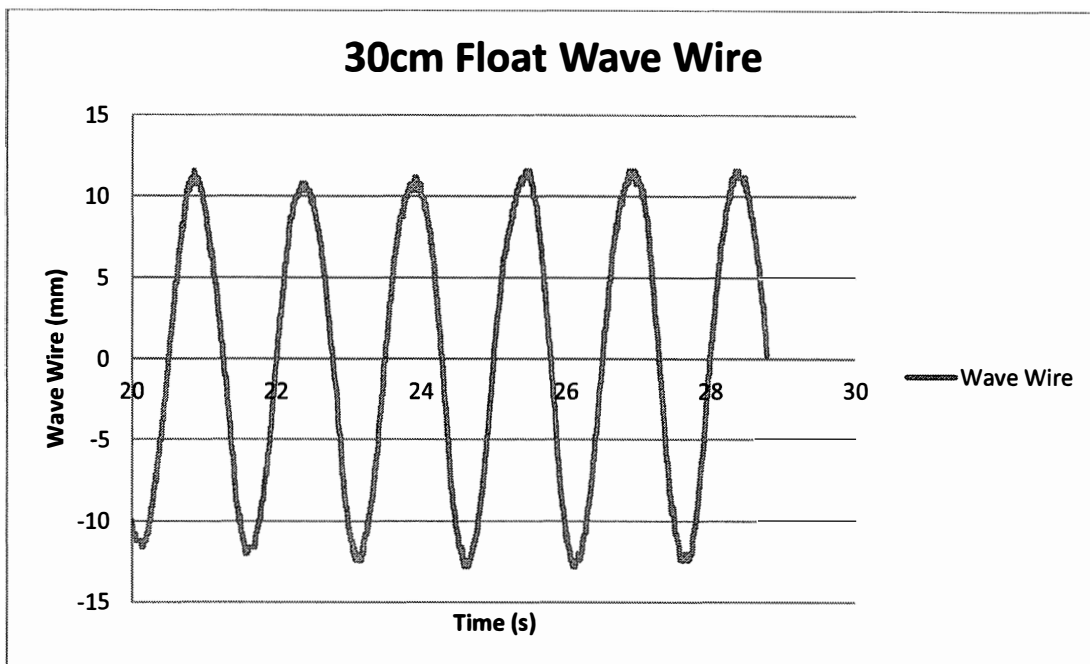
Figure 24: Wave wire data during 30cm diameter float measurements in Figures 22 and 23. The waves were monochrome 1.5s period with 1 inch (2.5cm) wave height

The incident wave power approaching the platform in Figures 21-24 was 0.927 Watts per meter (W/m) of wave crest across the tank. A 30cm diameter float moored upstream of the platform would have 0.278W of wave power acting on the mooring line. The theoretical maximum recoverable wave power in these conditions is 0.139W due to wave making resistance of a tethered float.

The float has a total volume of 0.014 cubic meters and 14kg of displacement when fully submerged in fresh water. The float weighs 2.7kg and the spring reel tether and load cell added 4kg to displacement. The float would displace 3kg above the static load (Fig. 23) a distance of 35mm per 1.5s wave cycle (Fig. 22). Total mechanical power imparted to the float-spring reel system was:

3kg x 9.8m/s^2 x 0.035m / 1.5s per wave = 0.233 Watts

This focusing of wave power has significant potential to increase the conversion efficiency of wave energy conversion systems.

Related Work

A hydraulic four-point mooring system is being fabricated for future tests (Figs. 25-26). This system will enable researchers to change depth and orientation of platforms during wave runs. Changing platform depth and orientation enables researchers to change the location of maximum wave height in the flow field.
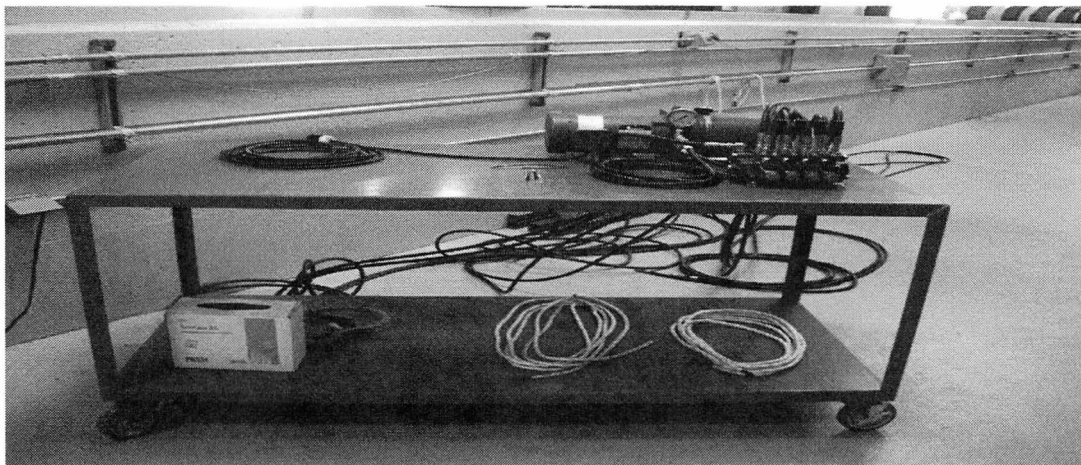
Figure 25: Hydraulic power-pack and 4-motor control valve mounted to the mooring system table
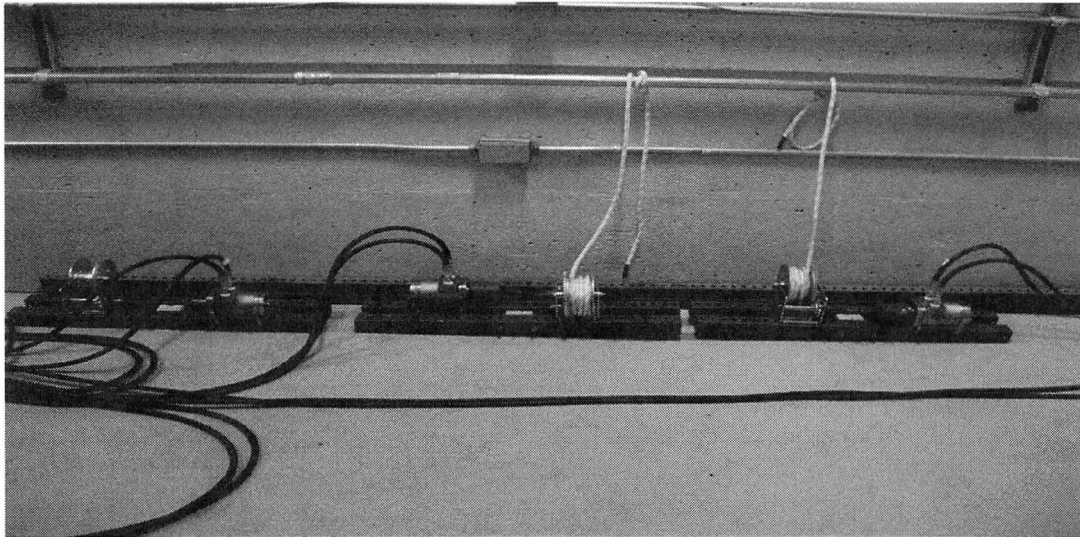
Figure 26: Hydraulic motors and braking winches mounted to square perforated tube for mounting on the unistrut™ channels in Tank 3

The high-density platform intended for testing in 2011 is not yet complete. The vendor contracted to fabricate the platform filed for bankruptcy, was unable to fulfill the contract, and returned the materials purchased for the platform to Stevens. PI Raftery has been reviewing hydraulic system manuals and consulting with engineers at Bosch-Rexroth to acquire the skills required to assemble the hydraulic power take-off and conversion system. High density platform fabrication has been incremental over the past year (Fig. 27).
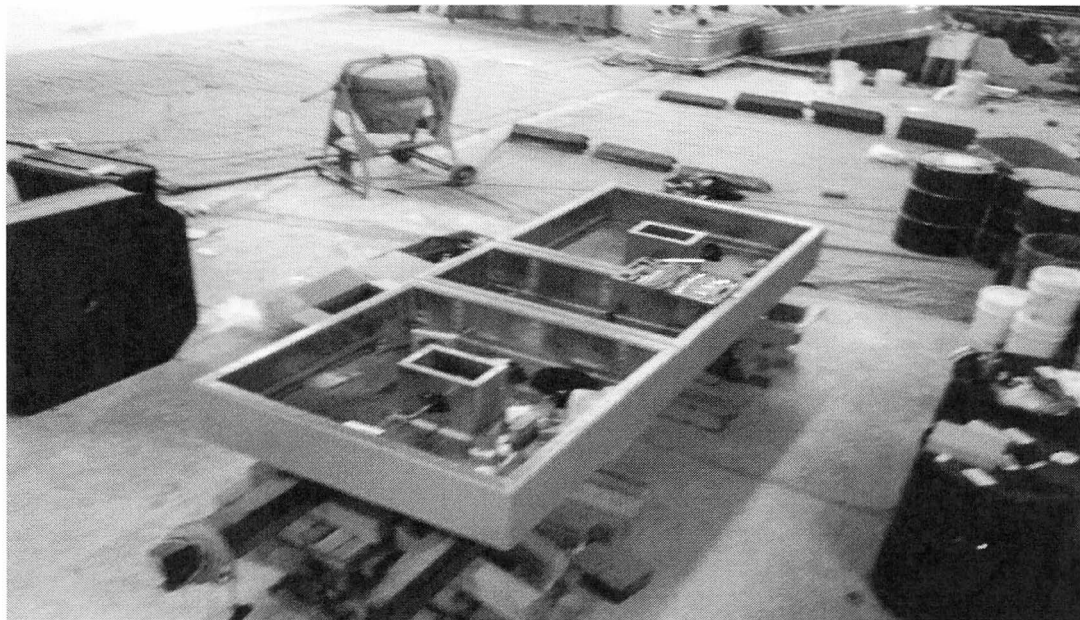
Figure 27: The high density TLP platform is being assembled at Stevens

Discussion

Fully submerged platforms have the potential to provide the U.S. Navy with marine renewable energy systems that will be deployable throughout the world's oceans, avoid extreme mooring loads in storms and focus surface wave energy onto power take-off components in mild wave conditions. The deployment process being developed for a full scale design is particularly well suited for littoral regions with silt or sand seafloors.

The variable depth platform has caused a four-fold increase in the wave energy density over the leading edge of the platform in some cases. Relations between platform depth, wave parameters, and wave energy density have been developed from the test matrix. Optimal depths for wave tuning have ranged from 2 to 4 times the incident wave height during tank tests. Optimization has been based on the maximum increase in wave height over the platform without a tethered surface float over this test period. Tethered surface floats complicate the optimization process, and actual power take-off from scale models will be required to provide data useful for design of wave energy conversion systems.

Future Work

Development and validation of CFD programs to simulate complex flow fields over submerged platforms will continue with expanded tests of various platforms.

Other Activities and Achievements

Students Involvement

Three students were involved in the set up and running of the position and load tests as part of their summer intern work. Two students worked during the summer processing the test data and contributed content to this progress report.

One PhD student was involved in the set-up of the position and load tests.

Publications

A presentation was published from the Marine Renewable Energy Conference on 2 November 2010 in Cambridge, Massachusetts sponsored by the University of Massachusetts at Dartmouth.

A presentation was published from the New York Institute of Technology conference held in Great Neck, New York on 2 June 2011

Interactions with Industry/Navy

Michael Raftery attended the Naval Science & Technology (S&T) Partnership Conference 8-10 November 2010 in Arlington, Virginia to pitch wave energy conversion research related to the current flow field research.

PI Raftery submitted a white paper:
"Underwater Wave Energy Converter Design Competition",
to the ONR STEM Forum on 16 June 2011 in an attempt to expand the work to other U.S. universities.

The PI has been in regular discussions with industry partners (Bosch-Rexroth and Airline Hydraulics) through periodic meetings and e-mail exchanges to discuss autonomous and remote depth control of the TLP and power take-off and conversion capabilities. When the power take-off and conversion and variable depth capabilities are integrated into a scale model platform, near shore power conversion, sea base, and stealth platform applications can be developed to meet US Navy mission requirements.

Supplemental Funding
The PI has received supplemental funding from DOD sponsors at the Picatinny Arsenal in New Jersey through an American Recovery Act program.

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14. ABSTRACT

Fully Submerged platforms have the potential to provide the US navy with marine renewable energy systems that could be deployable throughout the world's oceans, avoid extreme mooring loads in storms and focus surface wave energy onto power take-off components in mild wave conditions. The deployment process being developed for a full scale design is particularly well suited for littoral regions with silt or sand sea floors. A variable depth platform is tested in a wave tank and relations between platform depth, wave parameters and wave energy density have been developed. Optimal depths for wave tuning have ranged from 2 to 4 times the incident wave height.

15. SUBJECT TERMS

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INSTRUCTIONS FOR COMPLETING SF 298

1. REPORT DATE. Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

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